

# High-Energy Trauma and Damage Control in the Lower Limb

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## ABSTRACT

Management of traumatic lower-limb vascular injury can offer special challenges even to experienced surgeons. Recent U.S. conflicts have advanced the practice of vascular trauma surgery on the battlefield and offer important lessons learned for management of similar injury in urban trauma centers. Damage control techniques for complex injuries when associated with hemodynamic instability may provide an opportunity to save both life and limb. This article provides an overview of damage control principles in the management of high-energy traumatic vascular injuries of the lower limb during recent U.S. military combat operations.

**KEYWORDS:** Vascular trauma, massive transfusion, damage control, resuscitation, combat, wartime, military

U.S. military operations continue to advance the practice of vascular trauma surgery, and this has directly translated into current surgical practices used in urban trauma centers. Since the Vietnam War, there has been a considerable modernization of the battlefield environment that has translated into a measurable survival advantage.<sup>1,2</sup> Forward surgical support, expeditious evacuation, and effective resuscitation strategies have provided the foundation for recent innovative progress in the area of high-energy trauma and damage control maneuvers for lower-extremity hemorrhage.

Hemorrhage from extremity vascular injury remains a leading cause of potentially preventable death on the modern battlefield, and recent estimates suggest an increase in this injury pattern compared with that of previous wars.<sup>2,3</sup> Injuries of this severity cause an early and profound coagulopathy that is often present on admission to the emergency department.<sup>4,5</sup> Standard

damage control principles are routinely applied to achieve rapid hemorrhage control and to initiate a hemostatic resuscitation plan that will correct metabolic imbalances and prevent the onset or progression of a traumatic coagulopathy. Only when this life-saving sequence is properly executed can the military trauma patient be expected to withstand the metabolic perturbations of a complicated operation like extremity revascularization.<sup>6</sup> Damage control techniques, originally developed for unstable patients with abdominal injury, have been expanded to include patients with exsanguinating limb injuries.<sup>7</sup> Advances in evacuation, hemorrhage control, wound care, and other pioneering developments over time have shifted our past expectation of saving “life over limb” to the current goal of saving both “life and limb.”<sup>8</sup> The purpose of this article is to describe the management of high-energy trauma and crucial damage control techniques for lower-limb injuries.

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Extremity-Saving Surgery and Reconstruction: From Microsurgery Reconstruction to Transplantation; Guest Editors, Chih-Hung Lin, M.D., and Fu-Chan Wei, M.D.

Semin Plast Surg 2010;24:5–10. Copyright © 2010 by Thieme Medical Publishers, Inc., 333 Seventh Avenue, New York, NY 10001, USA. Tel: +1(212) 584-4662.  
DOI: <http://dx.doi.org/10.1055/s-0030-1253241>.  
ISSN 1535-2188.

<b>Report Documentation Page</b>			<i>Form Approved OMB No. 0704-0188</i>	
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1. REPORT DATE <b>2010</b>	2. REPORT TYPE	3. DATES COVERED <b>00-00-2010 to 00-00-2010</b>		
4. TITLE AND SUBTITLE  <b>High-Energy Trauma and Damage Control in the Lower Limb</b>			5a. CONTRACT NUMBER	
			5b. GRANT NUMBER	
			5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S)			5d. PROJECT NUMBER	
			5e. TASK NUMBER	
			5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) <b>Walter Reed Army Medical Center, Department of Surgery, 6900 Georgia Avenue NW, Washington, DC, 20307</b>			8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)			10. SPONSOR/MONITOR'S ACRONYM(S)	
			11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION/AVAILABILITY STATEMENT <b>Approved for public release; distribution unlimited</b>				
13. SUPPLEMENTARY NOTES				
14. ABSTRACT <b>Management of traumatic lower-limb vascular injury can offer special challenges even to experienced surgeons. Recent U.S. conflicts have advanced the practice of vascular trauma surgery on the battlefield and offer important lessons learned for management of similar injury in urban trauma centers. Damage control techniques for complex injuries when associated with hemodynamic instability may provide an opportunity to save both life and limb. This article provides an overview of damage control principles in the management of high-energy traumatic vascular injuries of the lower limb during recent U.S. military combat operations.</b>				
15. SUBJECT TERMS				
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT <b>Same as Report (SAR)</b>	
a. REPORT <b>unclassified</b>	b. ABSTRACT <b>unclassified</b>	c. THIS PAGE <b>unclassified</b>	18. NUMBER OF PAGES <b>6</b>	19a. NAME OF RESPONSIBLE PERSON

## INITIAL CONSIDERATIONS FOR HIGH-ENERGY, LOWER-EXTREMITY VASCULAR TRAUMA

Modern body armor modification that protects the chest and abdomen from projectiles and fragments has increased the number of service members with potentially survivable wounds. In concert with widespread prehospital tourniquet distribution, more casualties are now surviving the initial medical evacuation and presenting with severely injured limbs that prompt immediate limb salvage decisions in the midst of life-saving maneuvers (Fig. 1).<sup>2,9,10</sup> Optimal management requires proper planning and rapid recognition of the injuries requiring immediate treatment to prevent mortality from exsanguination. Military injuries often involve fractures, thermal injury, and embedded fragments over a majority of the body surface, in addition to blunt mechanisms of injury from high-energy blast effects. After immediate airway control, attention is directed at controlling hemorrhage and obtaining vascular access. Because immediate exposure of the entire patient is not always feasible in a combat environment and patients may arrive with one or more tourniquets on their extremities, external hemorrhage should always be considered as it can be more easily missed. Though direct pressure is the most effective way to control hemorrhage, a volume-depleted and profoundly hypotensive patient may not always manifest active arterial bleeding at the time of admission. Prehospital tourniquets should nonetheless be inspected and readjusted or replaced once the resuscitation restores adequate peripheral perfusion. For active arterial bleeding, the narrow prehospital tourniquets are commonly exchanged for the much wider Emergency & Military tourniquet (EMT) pneumatic type (Delfi Medical, Vancouver, Canada), and the wound is explored in the operating room.<sup>11</sup> Intravenous access may be hindered by shock, and immediate intraosseous access into the tibia or the adult sternum is easy and rapid. Initial



**Figure 1** Prehospital tourniquets have decreased hemorrhagic death on the modern battlefield and have increased the incidence of potentially salvageable lower-extremity vascular injuries. Damage control principles and advanced resuscitation strategies are employed to save both life and limb.

laboratory studies will depict the degree of physiologic distress that is used to guide the resuscitation and early operative planning.

Damage control resuscitation (DCR), a strategy of liberal blood product administration, minimal crystalloid use, and selective use of recombinant factor VIIa, should begin early in the emergency room and continue intraoperatively.<sup>12-14</sup> The goal is to achieve hemostasis, restore normal physiology, and potentially complete a vascular reconstruction upon arrival in the intensive care unit. Blood products should be transfused within minutes of arrival with an emergency release of 4 units of type O packed red blood cells (PRBCs) and 2 units of thawed AB plasma sent on demand from the blood bank. The blood products are best transfused through a Belmont rapid infuser system (Belmont Instrument Corporation, Billerica, MA) that is reserved in the admitting area. Unstable patients with a truncal injury or those with more than one mangled extremity are considered "in extremis" and should trigger a massive transfusion protocol. This involves a standardized release and transfusion of PRBCs, thawed plasma, cryoprecipitate, and platelets. We previously reported on clinical guidelines that advocated for earlier blood product administration and selective use of recombinant factor VIIa (rFVIIa) which normalized presenting physiologic derangement like heart rate, blood pressure, and base deficit. Early graft failures were not any greater with the selective use of rFVIIa for patients who required DCR.<sup>15</sup> However, for noncoagulopathic patients with isolated vascular injury, regional heparin is still preferred.

Rapid recognition of vascular injuries and the need for vascular reconstruction at the time of admission is crucial to the success of grafting and maximizes the chances of limb salvage. Knowledge of injury patterns and the vascular injuries with which they can be associated along with early detection of progressive limb ischemia are essential. Plain radiographs provide early reliable clues that extremity vascular injuries exist and therefore begin an important part of the developing plan for repair of a vascular injury. Supracondylar femur and tibial plateau fractures are frequently associated with injuries to the popliteal artery. Deformed extremities should be straightened, and the onset of additional hemorrhage is controlled with direct pressure, gauze packing, hemostatic dressings, or additional tourniquets. Alternatively, in stable patients, without active bleeding, prehospital tourniquets should be carefully loosened to determine the degree if any of vascular injury. A Doppler assessment is advised to confirm the absence of pedal pulses and to perform an Ankle-Brachial Index when possible. A patient assessment done in concert with an orthopedic surgeon will facilitate discussion regarding the sequence of surgical repair and preferred techniques for external fixation that best aid in the anticipated vascular exposure. Important information to relay early

to the entire operative team should include instructions for patient position, skin prep, vein harvest, and need for arteriography. Preferences for individually packaged instruments should be known to the surgical team. The most important pitfall to avoid is the unnecessary delay to the operating room. Radiographic assessment is not necessary for extremity vascular injury when hard signs are evident. The decision to initiate early resuscitation and obtain rapid surgical access to control the site of bleeding is the hallmark of success.

## DAMAGE CONTROL IN LOWER-LIMB VASCULAR INJURIES

Lower-limb vascular injury has the added challenge of not only controlling hemorrhage but also restoring blood flow to prevent limb-threatening tissue destruction. The patient should always be positioned to maximize access to all body cavities and extremities in the event of clinical deterioration or the need for additional autogenous vein conduit from another extremity. Ideally, initial control of hemorrhage is already accomplished on arrival to the operating room with tourniquets or hemostatic dressings. If this is not feasible, direct pressure remains a very effective means of achieving hemostasis. In the event that a provider is holding direct pressure over a significant vascular injury, the assistant's hand and arm should be prepped into the operative field and not moved. The injured vessel is then dissected proximally and distally while the assistant maintains direct pressure until proximal and distal control is obtained.

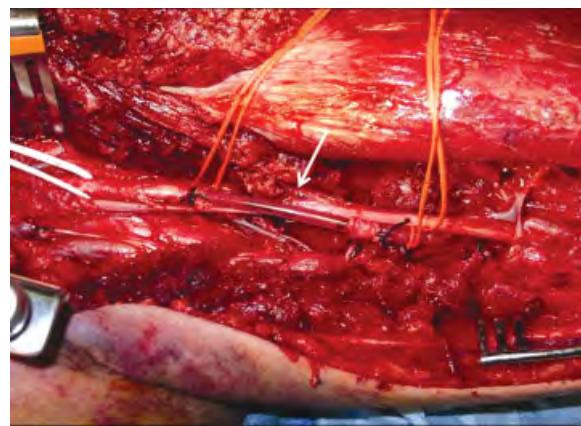
For noncompressible regions like the groin, deep thigh, or elongated missile tracts, extraluminal balloon tamponade can be a useful temporary measure to arrest bleeding and allow for careful dissection. A Foley urinary catheter can be inflated and sutured to the skin surface or reinforced using gauze packs for larger wounds. For inaccessible locations when the vessel is visualized but not easily controlled with vascular clamps or vessel loops, intraluminal balloons are very useful. For example, a Fogarty balloon may control troublesome back bleeding from a transected profunda femoral or distal popliteal artery and facilitate repair rather than resorting to ligation. Blind passage of clamps and other instruments in attempts to gain vascular control can often be unproductive and potentially cause injury to surrounding tissues. Many times, hasty blind dissection will worsen venous bleeding and is therefore discouraged.

If possible, a dedicated two-team approach is recommended for the operative management of multiply-injured patients with vascular injuries. For extremity injuries, this allows for early surgical treatment of the extremities while the primary surgical team is proceeding with thoracotomy, laparotomy, or other damage control maneuvers to achieve hemostasis. During this time, the second team can provide external fixation of long-bone

fractures, perform fasciotomies, perform arterial exposure to gain proximal and distal control of the injured vessel, or harvest autologous vein from an uninjured extremity. Care should be taken during fasciotomy to avoid injury to the greater saphenous vein when making the medial fasciotomy incision. The success of early damage control techniques is influenced by the ability to distinguish the simple from a complex repair and to apply the best strategy of ligation, repair, or temporary vascular shunting before the patient becomes physiologically exhausted.<sup>16</sup>

## Temporary Shunting

Shunts allow for perfusion during temporary delays needed for extremity fixation, or patient transport, or further resuscitation and have gained some popularity during the current conflict.<sup>1,17,18</sup> Eger and colleagues championed the notion of temporary shunting of combat-related arterial injuries in 1971.<sup>19</sup> Since that report, this practice has been supported by several small series from civilian trauma centers and is well summarized by Rasmussen and colleagues.<sup>20</sup> The potential for dislodgment, thrombosis, or reduced limb viability are obvious drawbacks and require good surgical judgment for effective use. Military operations in Iraq have produced the largest series of combat casualties since Vietnam and provide a renewed opportunity to examine the patterns of temporary shunt use and effectiveness. Data from the Balad Vascular Registry demonstrated that shunts placed in proximal vascular injuries have acceptable (86%) patency, and failure of distal shunts did not decrease limb viability.<sup>20</sup> Rasmussen et al concluded from this data analysis that the use of shunts was an effective technique to facilitate immediate evacuation and was preferable to prolonged reconstruction efforts in remote austere locations. Limb loss in the current conflict was



**Figure 2** Temporary shunting and delayed repair is preferred when in austere locations. An Argyle (Covidien, Mansfield, MA) shunt (white arrow) restores antegrade perfusion to the upper extremity after a high-energy wound with a brachial artery transaction. (Photo courtesy of Lt. Col. Todd E. Rasmussen, M.D.)

not associated with shunt thrombosis, and when shunt failure occurred, thrombosis was usually in distal vessels that could tolerate ligation.<sup>21</sup> The use of shunts has been a safe and effective damage control technique and may be preferable to attempted reconstruction when the physiologic condition or location of the patient is not desirable (Fig. 2).<sup>20</sup>

## METHODS OF VASCULAR REPAIR FOR LOWER-LIMB INJURY

Perhaps the most important step before selecting a method of arterial reconstruction is to ensure that the exposed artery is meticulously debrided back to normal and healthy-appearing tissue. High-velocity projectiles cause significant soft tissue injury that can extend well beyond the zone of obvious injury. The time spent on careful debridement will guard against repair in the setting of an unrecognized intimal injury or the onset of late infection from devitalized and contaminated soft tissues. Fogarty balloon catheter should be available, as prehospital tourniquets and incomplete heparin dosing in trauma may result in thrombus accumulation proximally. Retrograde advancement of a Fogarty catheter from an uninjured distal site can also be used to locate

the transected artery in a wound that is no longer actively bleeding. Although lateral repairs can be accomplished quickly, segmental loss is very common, and therefore a simple repair is usually not realistic in wounds from high-energy munitions. Dissection proximally and distally along the artery with division and ligation of nearby branches may provide enough mobility for a successful tension-free primary end-to-end anastomosis. If end-to-end repair is not feasible, interposition grafting using a saphenous vein graft from the contralateral limb is preferred when the clinical condition allows for the additional time that is necessary for a more technically demanding reconstruction (Fig. 3).

Prosthetic grafts have been discouraged for combat-related arterial reconstruction. Inferior long-term patency and the risk of graft infection have generally limited its widespread use in the management of extremity vascular injury.<sup>22</sup> In cases where autologous conduit is limited such as bilateral fragmentation, prosthetic grafts have been used successfully when interposed and covered by viable muscle tissue or routed extra-anatomically. Although long-term patency rates of prosthetics may be inferior to saphenous vein grafts, late thrombotic failures have not resulted in limb loss in our experience.<sup>23</sup>



**Figure 3** (A) High-energy munitions are associated with complex fractures and deep soft tissue wounds that frequently injure the artery and vein. (B) A popliteal to posterior tibial reversed saphenous vein graft harvested from the contralateral limb was routed medially away from the zone of injury to prevent graft contamination. (C) Vacuum-assisted closure (VAC) and placement of split-thickness skin grafts achieved early healing of this lower-limb injury as shown in (D) this 8-week follow-up photograph.



**Figure 4** Negative-pressure therapy has advanced the capability to close deep wounds that could otherwise risk a vascular graft dehiscence. This photograph shows that an external fixator will not preclude the ability to apply and effectively use the wound VAC.

Widespread application of negative-pressure wound therapy using vacuum-assisted closure (VAC System; KCI International, San Antonio, TX) has increased the enthusiasm for limb salvage in high-energy trauma of the lower limb.<sup>24</sup> In addition to aggressive debridement of all nonviable tissue and selective use of antibiotic beads, negative-pressure therapy has been instrumental in sustaining skin grafts and providing earlier closure of deep wounds that could otherwise risk vascular graft dehiscence (Fig. 4).

## PRIMARY AMPUTATION

The decision between limb salvage and amputation requires mature surgical judgment best achieved with experience managing these wounds in a combat setting. The location, available resources, severity of injury, and the overall condition of the patient are the obvious considerations. The Mangled Extremity Severity Score (MESS) is an objective method to predict favorable outcome based on age, degree of skeletal and soft tissue injury, duration of ischemia, and the presence of shock.<sup>25</sup> However, other civilian studies suggest that scoring systems have limited usefulness in predicting functional recovery after limb reconstruction.<sup>26</sup> In a recent report on military casualties from the United Kingdom, the MESS did not help to decide whether or not an amputation was appropriate, and, in particular, the age was not relevant. Most amputations in this U.K. study were performed when an ischemic limb was present, and the general condition of the casualty precluded the lengthy reconstruction required for salvage.<sup>27</sup>

## POSTOPERATIVE CARE

The goals of the early postoperative period are patient warming, resuscitation, and hourly vascular checks that should be performed with a hand-held continuous-wave Doppler probe. Palpable pulses and sometimes normal ankle-brachial ratios ( $>0.9$ ) may be delayed until an

appropriate resuscitation period has occurred. Patients should remain in the ICU for at least 24 hours. In addition to ensuring overall cardiopulmonary and metabolic stability, plans for evacuation out of the war zone should take the threat of early graft failure and post-operative bleeding into consideration. The vascular-injured patient should not be hurried unnecessarily through the chain of evacuation, as early graft- or repair-related complications may not manifest for as long as 24 hours. External fixators are readjusted based on the appearance of plain film radiographs, and a wound inspection is normally performed within 24 hours. The typical patient is returned to the operating room every 48 to 72 hours for additional washouts, debridements, and negative-pressure wound-dressing changes.

Development of compartment syndrome after repair of a vascular injury is a devastating complication. The use of regional anesthesia techniques further forward may make the pain of compartment syndrome less severe, and the compartment syndrome may develop during a prolonged aeromedical evacuation. As a result, immediate fasciotomies are recommended if there is a significant arterial injury or a mixed arterial/venous injury. Additionally, care must be taken to ensure that all four of the compartments of the leg are widely opened. The anterior compartment is the most frequently missed during fasciotomies, and loss of this compartment results in permanent foot drop and significant functional impairment of the extremity.

## CONCLUSION

The incidence of high-energy wounds of the lower limb has expanded the practice of vascular surgery on the modern battlefield. Extremity hemorrhage remains a leading cause of potentially preventable death. Optimal management involves rapid hemostasis and reversal of metabolic derangements using standard damage control principles. Damage control maneuvers and early initiation of damage control resuscitation may permit successful simultaneous limb salvage. These principles have been widely applied to military casualties in recent conflicts and are at least partially responsible for the significant reduction in mortality from previous wars.

## DISCLOSURE

The opinions or assertions contained herein are the private views of the authors and are not to be construed as official or as reflecting the views of the Department of the Army or the Department of Defense. The authors are employees of the U.S. Government. This work was prepared as part of their official duties and, as such, there is no copyright to be transferred.

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